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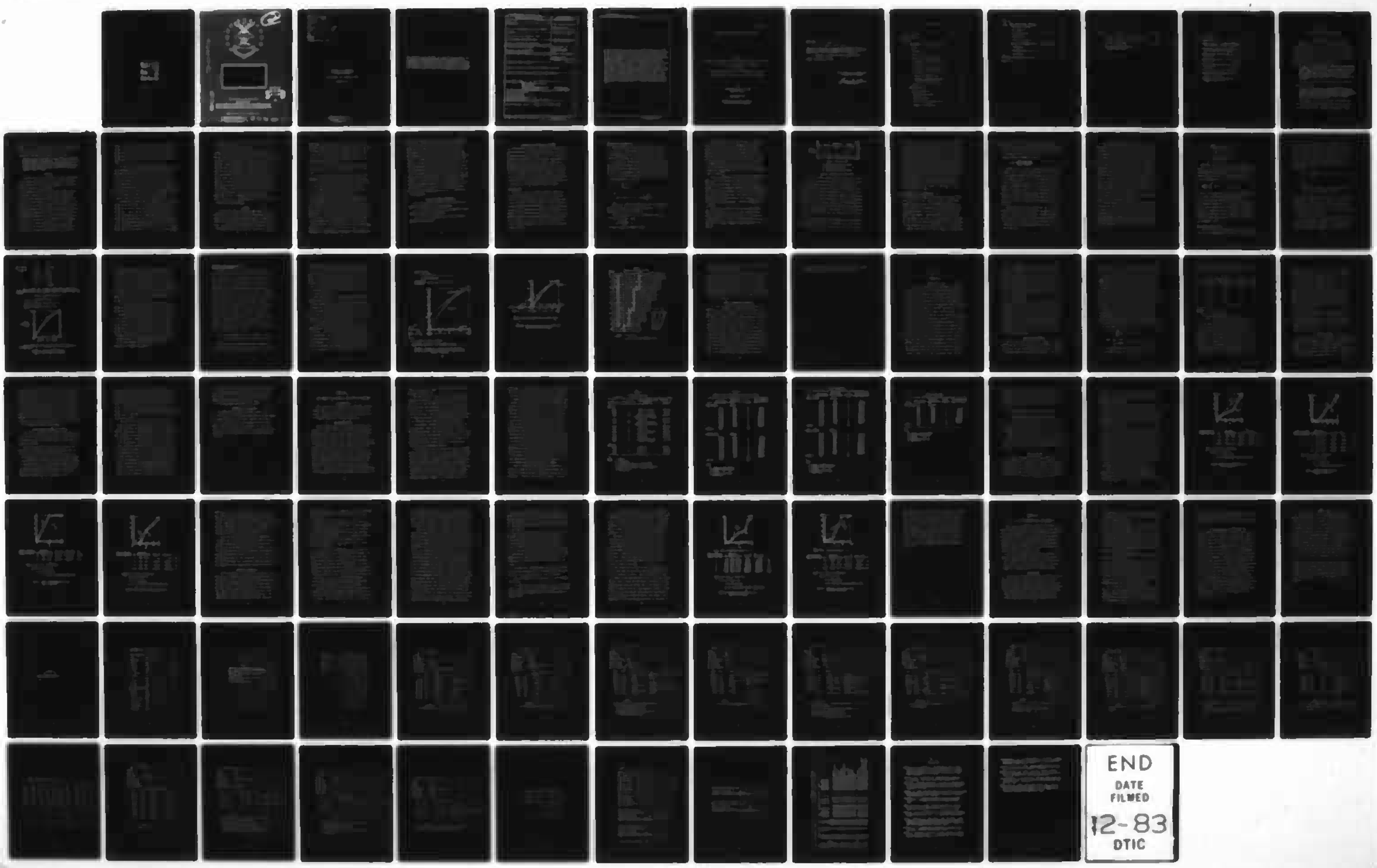

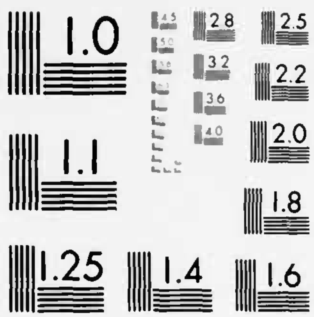

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PREVENTIVE MAINTENANCE
ON SPACE SYSTEMS

Joe Mariotti, Jr., Captain, USAF

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With the advent of an operational Space Transportation System, many opportunities for activities in space exist. Maintenance of on-orbit satellite systems is one such application. Planners need techniques to evaluate the appropriate maintenance category; i.e., whether a preventive maintenance program is feasible or should a corrective maintenance scheme be applied. This study demonstrates a simple yet technically accurate graphical estimating methodology, known as the Total-Time-on-Test plot. Specifically, using this technique in conjunction with on-orbit life data from Traveling Wave Tube Assemblies located aboard second generation Defense Satellite Communications System (DSCS-II) and North Atlantic Treaty Organization Phase III (NATO III) satellites, preventive maintenance on these items is shown not to be the method of choice. Further, techniques are demonstrated for determining estimated optimal maintenance intervals using failure and repair costs should preventive maintenance be demonstrated as a feasible maintenance category.

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PREVENTIVE MAINTENANCE ON SPACE SYSTEMS

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

Joe Mariotti, Jr., BA, MA
Captain, USAF

September 1983

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This thesis, written by

Captain Joe Mariotti, Jr.

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Issue

An operational Space Transportation System (STS) creates opportunities for activities in space that previously were not possible. The space shuttle, the primary launch system of the STS, serves to implement many aspects of the Military Space Doctrine, AFM 1-6. Specifically, it will provide a means of meeting the sustenance requirements established in AFM 1-6 which state that

> An integral responsibility to deploying a space force is maintaining it and ensuring that it has an enduring capability. Thus, the Air Force must develop a logistical capability to sustain forces that are based on the space medium. This logistics system should be developed and deployed concurrently with an operational capability. (U.S. Dept. of the Air Force, 1982, p. 4-10)

Maintaining systems within the space force would, by definition, include

> All actions necessary for retaining materials in or restoring it to a serviceable condition. Maintenance includes servicing, repair, modification, modernization, overhaul, inspection, condition determination, corrosion control, and initial provisioning to support items. (McCann, 1981, p. 407)

Maintenance may be classified into two categories: corrective and preventive maintenance. Corrective maintenance consists of all unscheduled maintenance actions

performed as a result of a component failure (or suspected failure) so as to restore the component to a specified operational condition (Blanchard, 1981, p. 19). Preventive maintenance, the second category, is composed of

> Equipment maintenance actions performed on a periodic basis, according to a specific set of instructions and a predetermined time schedule. The objective is to protect equipment capability and investment by removing the causes of failure and making adjustments to compensate for normal wear before failure occurs. (McCann, 1981, p. 536)

Problem

Given the capability to revisit and repair operational space systems, any decision related to space maintenance ought to begin by determining the appropriate maintenance category, corrective or preventive.

To address this issue, several other issues require resolution. First of all, do space system components exhibit failure patterns attributable to random failure? If random failure occurs (i.e., each like component, regardless of age has an equal probability of failure) then preventive maintenance would not improve component reliability. Here, we define reliability, $R(t)$, in the usual sense, as the probability that an item will perform adequately over a given time interval $[0, t]$. Reliability is a function of some time, t, and is calculated as $1 - F(t)$, where $F(t)$, the failure distribution, gives the probability of item failure occurring in the interval $[0, t]$ (Hillier &

Lieberman, 1980, pp. 594,605-606). Should a component exhibit a random failure pattern, the only maintenance program that would make intuitive sense would be a corrective maintenance scheme because a newly repaired or replaced item would have the same probability of failure as an old item.

If the failure pattern demonstrated wearout (that is as a component accrued more operating time its reliability decreased) then preventive maintenance may be in order. Maintenance planners would then be interested in determining an interval, or schedule, to accompany the preventive maintenance program. They would seek to determine an "optimum" maintenance interval; that is to say an interval which results in an optimal value of some management objective. Examples of some objectives include minimizing maintenance costs or maximizing item availability.

Maintenance planners need techniques that are straightforward and that provide accurate answers. Unfortunately, some of the current maintainability theory is difficult to implement. Often, typical maintenance models rely on specific knowledge of a failure distribution, which must be estimated from available data. There often is uncertainty as to the appropriate failure distribution which generates a like uncertainty regarding the model's accuracy. Moreover, these models often require users to have extensive knowledge

in the concepts and use of statistical techniques and optimization methodologies (Talbott, 1983).

Solutions exist to these questions and problems. For example, Barlow and Proschan (1965) develop several mathematical procedures to find optimum maintenance policies and intervals for a simple system. Barlow and Campo (1975) discuss a graphical method that displays operational failure data in a "Total-Time-on-Test" plot. This plot in essence is a transformation of the data's underlying failure distribution, F(t). This Total-Time-on-Test technique, (TTT), provides at a glance some insight into the appropriate maintenance scheme selection. Bergman (1977) incorporates maintenance cost into the TTT concept. With this addition, estimates of an optimum maintenance interval can be determined for Barlow and Proschan's Age Replacement Model. A description of these methods follows. We then apply Bergman's methodology to maintenance strategies for space systems.

Scope

Preventive maintenance may be appropriate for space satellites in that they are complex systems (i.e., composed of many subsystems and components) that might have components which exhibit wearout and failure due to operation. For example, the second generation Defense Satellite Communications System (DSCS-II) satellite has several

components which may exhibit wearout failures (versus random failures) while on orbit. These components include Traveling Wave Tube Assemblies (TWTAs), thrusters, batteries, and Despin Mechanical Assemblies (DMAs) (Byler, 1983). The modes of failure of these components on orbit are believed to be as follows:

1. TWTAs--separation of cathode coating from cathode causing defocus of the communications signal being amplified;

2. batteries--failure of the battery to recharge adequately given continual cycles of use and recharge;

3. thrusters--breakdown of the catalyst bed in which the fuel used in the thrusters is decomposed; and

4. DMAs--continuous operation of associated bearings and rotors causing wear (Byler, 1983).

We want to use graphical techniques rather than analytical techniques in resolving the questions concerning maintenance policy and interval determination because of three factors. First, graphical techniques can be used with scant data, as would be the case with high reliability components, such as those used in space systems, and yet that provide a technically accurate (albeit gross) estimate of an optimum maintenance interval. In estimating the optimum interval, the issue of the appropriate maintenance category (i.e., corrective or preventive) would also be addressed by these graphical techniques. Their simplicity

and intuitive appeal would be a second factor. Some non-graphical techniques require knowledge of the failure distribution, which in most instances will require a goodness-of-fit test to several typical distributions. The graphical approaches used in this study do not impose such a requirement in that they use only empirical component life data and cost estimates for preventive and corrective maintenance. No complex computations or statistical manipulations are needed with these graphical methods so as to greatly facilitate the maintenance planning. The third factor promoting the use of these graphical methods centers on their flexibility in evaluating potential future maintenance programs. Cost parameter uncertainty associated with new activities can be easily examined using graphical procedures which allow for simple sensitivity analysis.

Specific Problem Statements

The research seeks to answer two questions related to preventive maintenance of space systems:

1. Is preventive maintenance an appropriate category of maintenance for space systems?

2. If so, can an optimal interval be determined for scheduling maintenance?

Background and Literature Review

The concepts of complex structures and of reliability theory form the basis of optimum maintenance policies and maintenance interval determination. Here, we review these concepts as they apply to space systems. Specifically, models developed by Barlow and Proschan (1965) used in determining optimum maintenance policies are discussed. The graphical procedures introduced by Barlow and Campo (1975), and Bergman (1977) are then examined, with the intent of providing a working knowledge of how these procedures may be used in maintenance policy determination and in resolution of an optimum maintenance interval.

Space Systems

Space satellites are complex systems, composed of many individual components. The notion of complexity refers to the idea that each component may display individual operational and failure characteristics and that a system is composed of many components. As discussed below, the graphical techniques of Barlow and Campo (1975), and Bergman (1977) employ probability models of simple, single component systems. Space systems, then, may be thought of as a collection of these individual components (or single component systems) each with its own optimum maintenance interval.

Reliability and Failure

Each component in a satellite has its own reliability, $R(t)$, which, as noted by Hillier and Lieberman (1980), is the probability that it will perform adequately over a given time interval, $[0, t]$. A mathematical model of reliability, $R(t)$, can be developed based on the idea that an item may be of one of two states: good or bad. Given a random variable, T, associated with the time to failure of an item, let X represent a binary random variable indicative of the conditional state where 1 = good and 0 = bad in the interval $[0, t]$ such that

$$X = \begin{cases} 1 \text{ if } t \geq T \\ 0 \text{ if } t < t \end{cases}$$

and

$$R(t) = P(X = 1) = 1 - F(t) = \int_t^\infty f(y)dy \qquad (1.1)$$

where $P(.)$ indicates probability and $f(y)$ is the probability density function associated with $F(y)$ (Hillier & Lieberman, 1980, pp. 594-595,605).

"The failure rate, $r(t)$ is defined for those values of t for which $F(t) < 1$ by

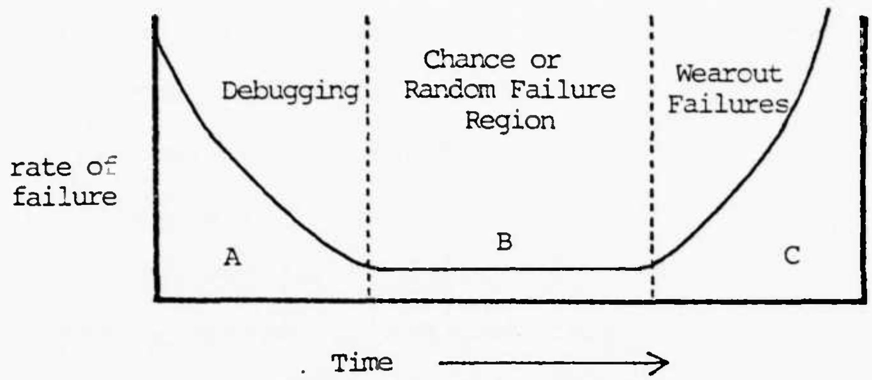
$$r(t) = \frac{f(t)}{R(t)} \text{"} \qquad (1.2)$$

(Hillier & Lieberman, 1980, p. 605).

An increasing failure rate (IFR) distribution is one where the failure rate, r(t), increases, or remains constant as age, t, increases. An IFR failure pattern typically occurs when failure is caused by deterioration through use or wear. Conversely, a distribution with a failure rate that remains constant or decreases with age is termed a decreasing failure rate (DFR) distribution. Such a distribution would be applicable to items whose reliability improved with age or use (Hillier & Lieberman, 1980, pp. 605-606).

There are components that have a failure distribution that is both IFR and DFR; in other words, they have a "constant" failure rate. In this situation, such components are said to exhibit exponential reliability because the exponential distribution is the only distribution which has a constant failure rate. The exponential distribution represents the "natural bounds on the survival probability of IFR and DFR distributions" (Hillier & Lieberman, 1980, p. 606).

These three classes of failure rate distributions may be plotted as a function of time. Such a plot is commonly referred to as the bathtub curve and is illustrated as Figure 1. Each of the three failure rate distributions, as shown, occupy distinct portions of the curve.



A: Decreasing Failure Rate (DFR)

B: Constant Failure Rate

C: Increasing Failure Rate (IFR)

Figure 1. Bathtub curve (Zambo, 1980)

Early failures, those occurring in the initial portion of the bathtub curve, denoted as Region A in Figure 1, are also termed infant mortality or infant failures. Experience has shown that DFR class distributions model the failure patterns of components subject to premature failure. To eliminate these early failures, many manufacturers subject these components to a burn-in or debugging operation whose duration corresponds to the DFR portion of the bathtub curve. Subsequently, these burn-in components are incorporated into an end item or used in an application by the user (Shooman, 1968, pp. 171-172; Zambo, 1980, pp. 20-23).

Preventive maintenance is appropriate in situations where the failure rate is increasing; i.e., where an IFR class distribution is demonstrated. The intuition behind

this statement may be seen by considering the alternate case in which components exhibit DFR class (including exponential failure) distributions. First, given that a DFR life distribution component is replaced, the replacement component has a higher probability of failure than the original component (recall, DFR components improve with use). Similarly, if the component has an exponential life distribution, an analogous situation exists in that a new item is no better or worse than a used item; therefore, there may be no benefit to be gained by replacing components displaying either a DFR class or exponential failure distribution. In these alternate situations, corrective maintenance would be the maintenance method of choice (Talbott, 1983).

Optimum Maintenance Policies

Barlow and Proschan (1965) discuss several optimum maintenance policies. These are based on probability models which minimize cost or maximize availability and are divided into two categories: replacement models and inspection models, the later of which are also termed preparedness models. Both type models employ the two-state concept of an item; i.e., it is either good or bad. Renewal theory is also a central factor in each. The concept of renewal refers to any process, i.e., replacement or repair, that returns an item to a good-as-new condition.

A key result of renewal theory can be summarized in the statement that says the average long-term reward per unit of time, C(t), is a function of the expected reward in the renewal cycle divided by the expected renewal cycle length as demonstrated in Equation 1.3 below.

$$C(t) = \frac{\text{(Reward/Cycle)}}{\text{(Cycle Length)}} \tag{1.3}$$

Reward may be in terms of availability or some other measure such as a negative reward like cost. Accordingly, we would seek to optimize the reward by maximizing benefit or minimizing cost. Cost may be monetary in nature or may be interpreted as the time to replace a failed component or nonfailed component. The Mean Time to Repair, (MTTR), is an example of the later interpretation in which the time involved in repair actions following a specific component's failure could be greater than the repair time that would have been associated with replacement prior to failure.

Replacement policies and inspection policies differ depending on whether item inspection is required to determine its state (i.e., good or bad). Replacement models assume an item's condition is known without inspection, while conversely, inspection policies require that an inspection of the item be accomplished in order to determine its state.

Two fundamental replacement models are the Block Replacement model and the Age Replacement model. These models differ in their respective approaches to the timing of replacement. In Age Replacement policies, components are replaced at failure or at age T, whichever occurs first. Note that T and the failure time may coincide. T is generally taken as a constant, however, it may be independently chosen from a fixed distribution for each scheduled replacement, in which case, the associated maintenance policy would be termed a "Random Age Replacement" policy. Alternatively, Block Replacement models use fixed time intervals for replacement regardless of component age as well as replacement of failure and consequently, as discussed by Barlow and Proschan, are more wasteful of good components than an Age Replacement policy. Block Replacements, however, lower the number of failures in comparison to Age Replacement policy use.

Age Replacement models are used in graphical methods, as discussed below, in determining the optimum maintenance interval. To reiterate, in Age Replacement, items are replaced at failure or at age T, whichever occurs first. Age Replacement is appropriate for components displaying IFR class failure distributions. Equation 1.4 provides the optimum replacement interval in terms of T, the Replacement Age.

$$C(T) = \frac{C_1F(T) + (C_2R(T))}{\int_0^T R(x)\ dx} \quad . \tag{1.4}$$

where C_1 = failure costs, and

C_2 = replacement costs.

Note that C(T) in Equation 1.4 is equivalent to C(T) of Equation 1.3. The respective numerator and denominator expressions are also equivalent. Using first order optimality conditions, Barlow and Proschan (1965) show that an optimal Replacement Age, T, must satisfy Equation 1.5.

$$\frac{F(T)}{1-F(T)} \int_0^T (1-F(t)dt - F(T) = \frac{C_2}{C_1 - C_2} \tag{1.5}$$

Equation 1.5 is applicable when the failure distribution, F, is known. The actual distribution, however, is rarely known with certainty (Barlow & Proschan, 1965).

Inspection policies, as noted, apply to components which require inspection to determine their condition. Models for inspection policies are generally more complicated than replacement models. Moreover, graphical techniques for these models have yet to appear in the literature (Talbott, 1983).

<u>Total-Time-on-Test Plot</u>

Barlow and Campo (1975) develop a graphical method that aids in the determination of the failure distribution

of a component using empirical, i.e., observed, data. Their technique, called the Total-Time-on-Test plot (TTT), begins by ordering a number of independent lifetimes, X_i, an item on test. The data, say n observations, would be ordered from shortest lifetime, say represented by $X_{(1)}$, to the longest lifetime, say represented by $X_{(n)}$. The total-time-on-test statistic through the ith failure is calculated as:

$$T(X_{(j)}) = \sum_{j=1}^{i} (n-1+j)(X_{(j)} - X_{(j-1)}) \qquad (1.6)$$

where

$T(X_{(0)}) = 0$,

$T(X_{(i)})$ = the total-time-on-test statistic, and

$X_{(i)}$ = the ith independent lifetime.

The ratio of $T(X_{(i)}/T(X_{(n)})$, designated U_i, is called the scaled total time on test at age $X_{(i)}$. It provides the vertical axis of the TTT plot. The ratio i/n provides the similarly scaled horizontal axis. The scaled TTT plot is therefore a plot of U_i versus i/n. Figure 2 illustrates the construction of a TTT plot.

Use of TTT plots allows easy identification of IFR and DFR distributions. A constant failure rate distribution, or exponential distribution, is represented by a straight 45 degree line commencing at the origin and

ith Failure	$X_{(i)}$	$T(X_{(i)})$	U_i	i/n
1	5 hrs	20 hrs	.4	.25
2	10 hrs	35 hrs	.7	.50
3	15 hrs	45 hrs	.9	.75
4	20 hrs	50 hrs	1.0	1.00
		(n = 4)		

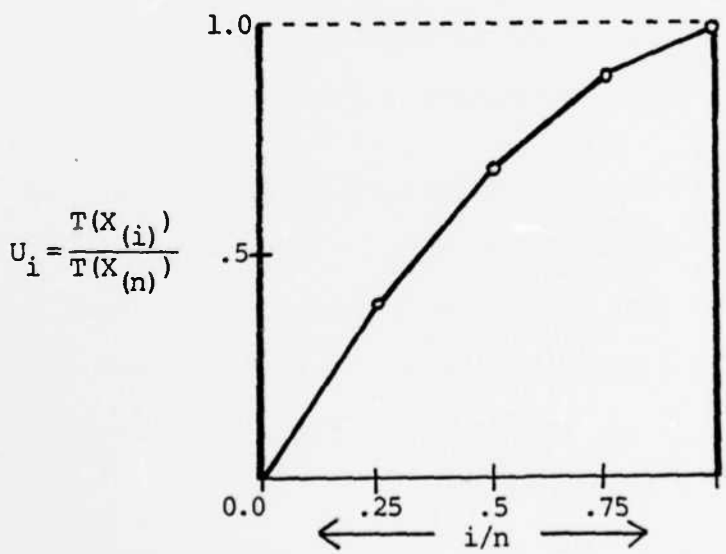
Note: Lifetimes, $X_{(i)}$ have been ordered prior to computations. Sample computations for the $X_{(1)}$ failure given the formula for total-time on test

$$T(X_{(i)}) = \sum_{j=1}^{i} (n-j+1)(X_{(j)}-X_{(j-1)})$$

$T(X_{(1)}) = (4-1+1)(5-0) = 20$ hrs.

$U_i = T(X_{(1)})/T(X_{(4)}) = 20$ hrs/50 hrs = .4.

where i = 1 and n = 4, i/n = 1/4 = .25.



Note: Sample TTT plot displays convex curve indicative of an IFR distribution.

Figure 2. Use of the TTT plot
(adapted from Talbott, undated)

proceeding up and right. Should the TTT plot represent an IFR distribution, it would be distinguishable by its convex shape; that is, bowed up in relation to the horizontal axis as the plot proceeds from the origin to the upper right corner of the scale. The TTT plot represented in Figure 2 provides an example of such a shape, indicating that the item generating the lifetime data has an IFR distribution. Conversely, a DFR distribution is concave in shape, that is, identifiable by its cup-like downward bow towards the horizontal axis.

TTT plots allow analysis of failure distributions when only incomplete data are available which is an important feature. Incomplete data can consist of three types: (1) grouped data, (2) truncated data, and (3) censored data. Grouped data records failures in terms of the number of failures that occur within a specified time interval. Truncated data occurs when observation, or data recording, is terminated at an arbitrary time. Censored data involves the termination of data collection after a specified number of failures. Each of these types of incomplete data can be addressed by modifying the TTT plot construction through the total-time-on-test equation, Equation 1.6 (Barlow & Campo, 1975).

Bergman's Technique for Solving Age Replacement Models

Bergman (1977) estimates the optimum replacement interval using the TTT plot technique and a standardized cost relationship. His technique has the advantage of not being constrained to a known failure rate distribution. The standardized cost relationship is developed from the reasoning that an item may demonstrate a proneness for failure as a function of its state (e.g., wear). Knowledge of the item's state may reveal a dangerous condition should it be allowed to fail. One method of obtaining this knowledge would be by tracking hours of operation, distinct from merely noting a component's age in that the later may reflect total installation time, of which, actual operation may be but a portion. Now, suppose each failure costs C_1 and each replacement costs C_2. Preventive maintenance is reasonable only if C_1 is greater than C_2. Consequently, each failure may be associated with a cost K added to a replacement; i.e., $C_1 = C_2 + K$. A standardized cost, C, can be derived as follows:

Let C, the standardized cost of replacement = C_2/K;

$C + 1$, the standardized cost of replacement = C_1/K.

Bergman plots the standardized cost of replacement, C, on the horizontal axis of the TTT transform. He locates it to the left of the transform's origin at $-C$. A line

may be constructed from -C tangent to the point on the TTT plot that yields the greatest angle as measured from -C and the horizontal axis. A line drawn vertically from this tangent point to the horizontal axis reveals the index, i, of the optimum interval. The estimate of the optimum interval is the ith component lifetime (Bergman, 1977). Figure 3 illustrates the construction and use of the standardized cost of replacement factor, C, in conjunction with the TTT plot.

The simplified construction of the standardized cost relationship promotes its use in conducting sensitivity analysis (Bergman, 1977). This process is especially valuable when considering the uncertainty associated with cost estimates for future programs such as those associated with space activities. A demonstration of sensitivity analysis using the TTT plot and the standardized cost factor is provided in Figure 4 and Table 1.

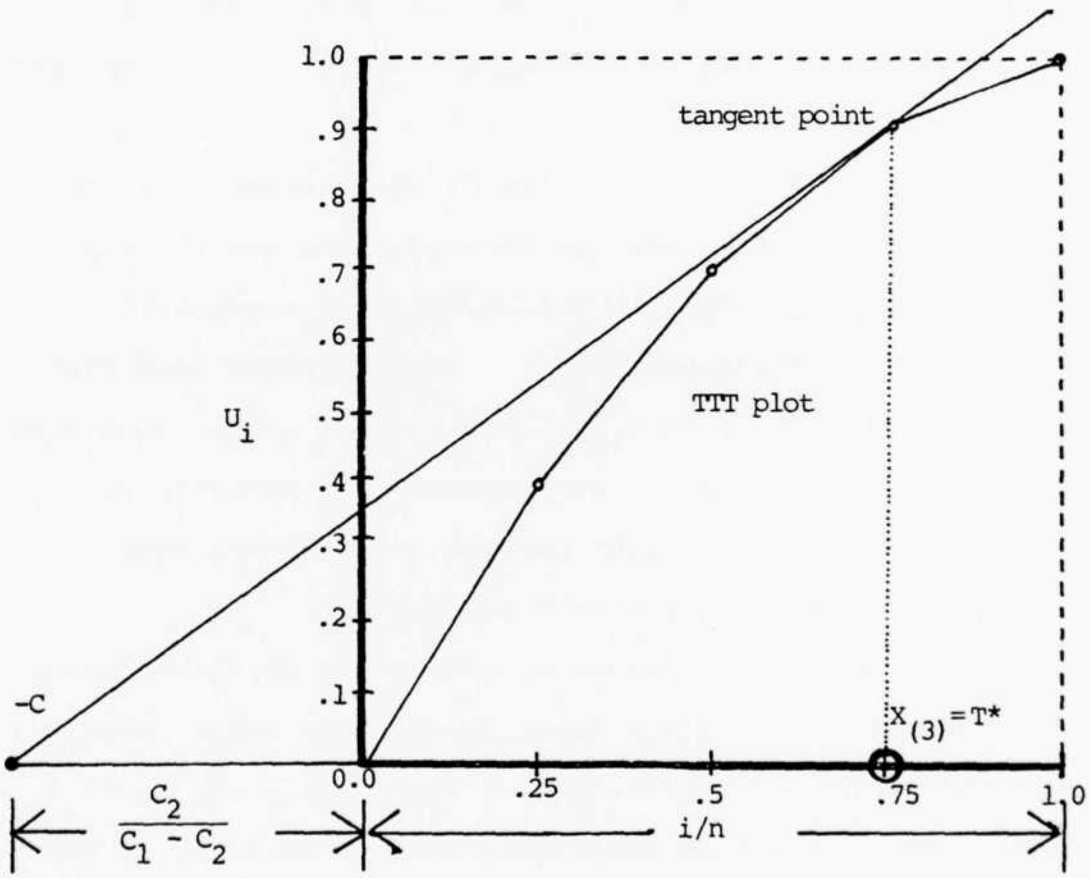
Lines B and C of Figure 4 demonstrate which values of standardized cost provide alternate optimum maintenance intervals. Line A is the tangent line from point -C = -.5 to the TTT plot and is associated with an estimate of the optimal maintenance interval of 15 hours. For any value of C between -.4 and -.1, the optimum interval will be 10 hours, as derived from tangent line B. A standardized cost, C, greater than -.1 will result in a different

Given costs are:

C_1 (Failure Cost) = \$15

C_2 (Replacement Cost) = \$5

Standardized Cost Factor $- C_2/(C_1 - C_2) = -\$5/(\$15 - \$5) = -.5$

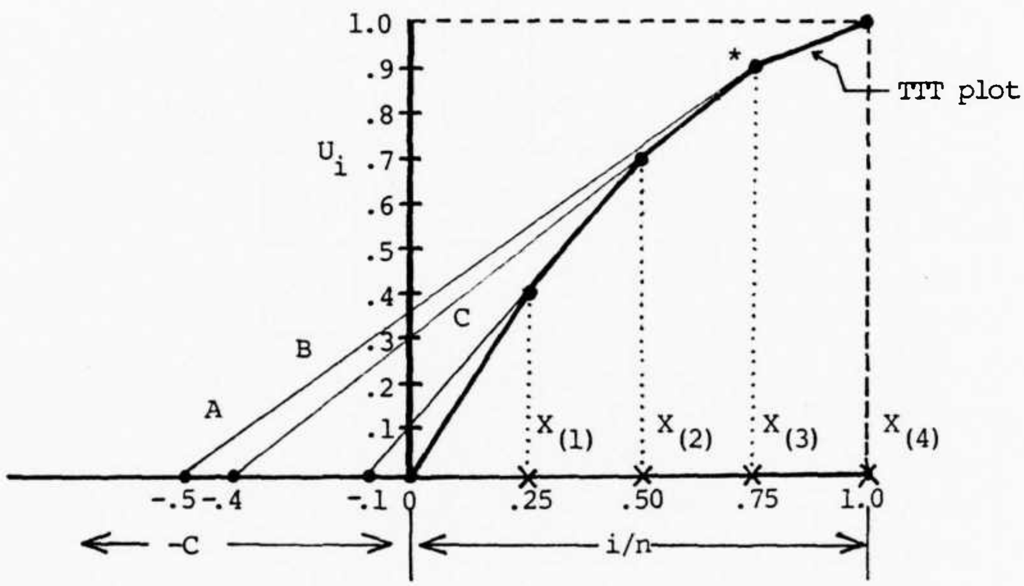


Notes:

T* = optimal replacement interval.

Hypothetical data for TTT plot provided with Figure 1.

Figure 3. Bergman's graphical technique using the standardized cost relationship (adapted from Talbott, undated)



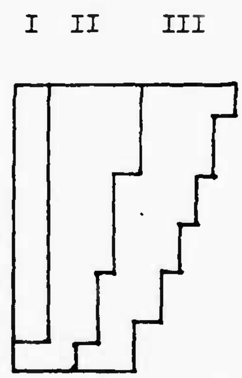
<u>Note</u>: * Original optimum interval tangency point.

Figure 4. Sensitivity analysis using the TTT plot and standardized cost factor

Table 1

Sensitivity Analysis Matrix

C_1\$ \ C_2\$	1	2	3	4	5*	6	7	8	9	10
20	.053	.111	.176	.250	.333	.429	.538	.667	.818	1.0
19	.056	.118	.188	.267	.357	.462	.583	.727	.900	
18	.059	.125	.200	.286	.385	.500	.636	.800	1.0	
17	.063	.133	.214	.308	.417	.545	.700	.889		
16	.067	.143	.231	.333	.455	.600	.777	1.0		
*15	.071	.154	.250	.364	.500	.667	.875			
14	.077	.167	.273	.400	.555	.750	1.0			
13	.083	.182	.300	.444	.625	.857				
12	.091	.200	.333	.500	.714	1.0				
11	.100	.222	.375	.571	.833					
10	.111	.250	.429	.667	1.0					



Note: $-C = -C_2/C_1 - C_2$

* = original values of Figures 1 and 2

optimum maintenance interval, as derived from tangent line C, corresponding to $X_{(1)} = 5$ hours.

Table 1 demonstrates how various values around those provided for C_1 and C_2 may be used to construct a matrix to gauge the standardized cost relationship factor's effect on the optimum maintenance interval given different expected values for the original costs. The matrix is divided into three segments, I, II, and III corresponding to the respective optimum intervals of component lifetimes $X_{(1)}$, $X_{(2)}$, and $X_{(3)}$.

Specific Research Questions

We seek to determine first whether preventive maintenance is an appropriate category of maintenance for space systems, and, secondly, given that preventive maintenance is an appropriate maintenance approach, can optimal maintenance intervals be determined for use in a scheduling plan? Given a positive response on the two initial research questions, additional issues may surface. Specifically, noting the complex nature of space systems, can individual component replacement times be grouped in such a manner to provide an optimum maintenance interval estimate for subsystems or systems? Also, provided the issue of preventive maintenance is appropriate and data for the associated cost analyses are available, are the cost parameters flexible enough to account for the uncertainty

associated with future space efforts, and yet exact enough to provide reasonable estimates usable by planners?

CHAPTER II

METHODOLOGY

Data Collection

Operational data used in this study were obtained from the Space Division of the Air Force Systems Command. It consists of component life data from the DSCS-II and the North Atlantic Treaty Organization Phase III (NATO III) defense communications satellites. The components were selected on the basis of a suspected wearout mechanism as discussed in Chapter I, and the availability of corresponding historical data of their on-orbit operation.

Operational data consists of the operational time-on-orbit of the various components. Specific failure times are tracked for each serially numbered component. These components are believed to represent like components used on other systems, both in function and in wearout modes. Operational data, then, are ordered in terms of lifetimes and are used to construct a total-time-on-test statistic for each component following Bergman's technique. For example, lifetime data for Expanded Earth Coverage High Level-20 watt TWTAs that have logged operating time are extracted and converted into a total-time-on-test statistic. A TTT plot is then constructed using this data.

Use of satellite component data involves incomplete data which we discussed earlier with the TTT plotting technique. Incomplete data is due to the fixed, monthly period associated with the satellite system status report which represents a snapshot of both failed and active components. Because system components are still operational, i.e., not all the individual components have failed, the data is "incomplete" and the TTT plotting technique alteration is needed. The appropriate modification is discussed under model development.

The remaining data will be collected and used provided the initial feasibility of preventive maintenance is demonstrated. This data would consist of the cost estimates necessary to formulate the standardized cost relationship developed by Bergman (1977). This cost data would represent the costs of component failure and the costs of replacement. As previously discussed, this data may be composed of two types. It may be either the monetary cost or costs in terms of the applicable mean times to repair (Barlow & Proschan, 1965).

Developing the Model

As previously indicated, a TTT plot using incomplete data should be used to analyze space system data. Specifically, we use a method advocated by Barlow and Campo (1975) and termed the truncated data method. Under this

method, k is used to represent the number of components that have failed up to the time of the system status report, L, while n represents the total number of like components, both failed and operational. This includes those components that have prior operational time yet may have been turned off purposefully or whose operational monitoring is possible even though the host satellite is considered nonfunctional. As with TTT plots computed from complete data, the truncated method requires that the failures be ordered, shortest lifetime to longest. The specific $T(X_{(i)})$, the total-time-on-test statistic for the individual components, is computed differently, however. It is the cumulative total of the lifetimes of both the previously failed components and the cumulative lifetimes of those components yet operational at the ith failure. A truncated total-time-on-test statistic, T(L), replaces $T(X_{(n)})$ in Equation 1.6 and represents the cumulative operational time up through the last failure, so that

$$T(L) = \sum_{j=1}^{k} (n-1+j)(X_{(j)} - X_{(j-1)}) \tag{1.7}$$

where $X_0 = 0$ and

k = number of failures in interval [0,L].

The scaled total-time-on-test statistic, U, is constructed as $T(X_{(i)})/T(L)$, while the ratio of i/n is

replaced by i/k. An example of the formulation of a TTT plot using the truncated data modification is at Table 2.

Table 2

TTT Plot Formulation Using Truncated Data

n	$X_{(i)}$	$T/X_{(i)}$ hrs	$U_{(i)}$	i/k
1	5	30.0	.39	.25
2	7*	40.0	-	-
3	10	52.0	.67	.50
4	15	67.0	.87	.75
5	20	77.0	1.00	1.00
6	22*	-	-	-

Notes:

k = 4 = failed components.
* = non-failed component.
n = total no. of operational components = 6.

The similarities between the truncated data formulation of Equation 1.7 and the complete data TTT plot as shown in Figure 1 are readily evident. Recall, since component 2 in the truncated data example did not fail, correspondingly, a computation for U_i was not needed. However, the cumulative effect of component 2's operational life is felt by subsequent computations through the total-time-on-test statistic. Also, since component 6, another non-failed device, continued to operate past the data

collection cutoff, there is no need to include its contribution of operational time to the total-time-on-test statistic beyond that accumulated at the time of the last failed component (i.e., component number 5).

Should the satellite component TTT plots show preventive maintenance to be a potential maintenance alternative for satellites it will require grouping of the different component total-time-on-test computations into various aggregates in order to evaluate subsystems and systems. Such an overall evaluation method would be accomplished by formulating an aggregate total cost function representing subsystem or system costs.

A key aspect of standardized costs is that it facilitates sensitivity analysis. The uncertainty associated with these estimates points out the merit of using the graphical techniques since they allow an estimated optimum replacement interval range to be constructed using best and worst case estimates.

Sampling Issues

Because the TTT plot is a transform of the failure distribution of the sample, the estimate of the optimum interval is in turn linked to the sample. Singpurwalla and Talbott (1981) discuss this matter: "Limited time on test data may not adequately represent the true failure distribution thereby inducing sample error" (p. 10). However, they

go on to state the following: "This difficulty surfaces any time life data from a sample is used to make inferences about a population of items" (p. 10). As more data are collected, the estimate of the optimum interval will become increasingly accurate. Consequently, the best graphical estimate is gained by use of all the life test, operational data available at that specific point in time (Talbott, 1983). Since satellites are composed of high-reliability components and complex structures, we can expect the issues connected with low numbers of failures over extended operational periods to surface in this study.

Fulfilling the Research Objective

The use of the graphical techniques of Total-Time-on-Test plots in conjunction with Bergman's standardized cost relationship factor will provide answers to both major problem statements.

Referencing the primary question of preventive maintenance as an appropriate maintenance category, the TTT plot provides a simplified straightforward visual resolution of the problem. Graphically transforming the underlying theoretical distribution of the component or system failure distribution to a correspondingly shaped TTT plot, the question of preventive maintenance as an appropriate maintenance methodology can be discerned. TTT plots revealing a convex shape are reflective of data

demonstrating an underlying IFR distribution. Such a distribution would support consideration of a preventive maintenance scheme in response to the empirically evidenced wearout of the particular item or system. Similarly, a DFR or exponential distribution plot can also be easily identified by the respective concave shape or 45 degree plot. Empirical data resulting in TTT plots demonstrating these later shapes would naturally suggest corrective maintenance programs.

Should the TTT plot display an IFR distribution, thereby indicating the applicability of a preventive maintenance approach, the second problem statement, how might such a maintenance policy be scheduled, can be addressed. The procedure, as discussed, would involve the search for and collection of appropriate cost data in order to conduct cost analyses in conjunction with the applicable TTT plots. Bergman's technique for computation and use of this indicator provides a technically correct yet uncomplicated method for determining the estimated optimum maintenance interval. The accuracy of this estimate has been noted to be dependent in part on the exactness of the cost data. A key feature of this graphical approach is its inherent flexibility for conducting sensitivity analysis which will allow planners or managers the ability to manipulate cost parameters among all the estimated values.

If preventive maintenance is determined to be feasible and an associated optimum replacement interval computed, management may then apply the associated costs and time factors to other organizational constraints or program goals not addressed in the graphical methods.

Summary of Assumptions

We assume that the sample data are representative of lifetime data on like components that might be incorporated into space systems of the future. Further, should the results of the initial TTT plot analyses warrant maintenance interval evaluation, the assumption of costs considered as constant applies to the use of Bergman's graphical method in the determination of an optimum maintenance interval.

CHAPTER III

DATA DESCRIPTION, ANALYSIS, AND COROLLARY FINDINGS

Introduction

Here we present the results of our analysis. We begin with discussion of the specific data as it relates to the Bergman's graphical technique. We follow with the analysis and finally present some corollary results.

Data Description

The data were provided by the Space Division of the Air Force Systems Command. We selected several candidate components in the belief that they would perhaps exhibit a wearout failure mechanism. These components are TWTAs, thrusters, batteries, and DMAs. A search by Space Division for operational, on-orbit, data related to these components yielded but one positive finding. TWTAs were the only component of the requisite type with the necessary life data available. Consequently, the scope of this research became considerably narrowed to this one component type. Data on TWTA on-orbit operation was extracted from the monthly TWTA Statistics report published by the Space Division. The various analyses reported herein have drawn all the requisite data from this document (specifically the

1 March 1983 report). This document is included as the Appendix to this study.

The TWTA Statistics report contains operational data from three satellite programs which are: (1) the DSCS II, (2) DSCS III, and (3) NATO III programs. DSCS II TWTA data, carried under satellite program 777, include data on 11 satellites. A second DSCS satellite program, DSCS III, has one satellite. The third satellite program included in the report is the NATO III defense communications satellite, which has three operational satellites listed.

Our analyses includes both the DSCS II and the NATO III satellite. Since only one satellite of the DSCS III type was operational, the usefulness of its data was viewed as limited and is not included in this research. An additional reason for its exclusion was lack of design commonality with DSCS II TWTAs, which would preclude its inclusion in any aggregate analysis.

The data consist of the operational hours as listed under the individual satellite report category of OP TIME/HRS TWTA FAIL DATE. Post launch checkout operating time was not included in the operational time total because we felt this alternate operating time was not analogous in all aspects to the on-orbit operational time. Carried as commentary to each satellite, the various post launch checkout times were not included as inputs to the TWTA Statistics report on-orbit operating time totals, and

additionally, in no instance did it correspond to more than 5 percent of the satellite operating time for those satellites that had recorded TWTA (mission) operating hours.

Statistics related to the satellites themselves are in Table 3, and include information such as launch date, current satellite status (as of the 1 March 1983 report) and satellite operational time. Satellite operational time may not necessarily equate to the total operational time noted for a given TWTA type. Given a functionally failed satellite, TWTA monitoring may have continued in order to gain component operational life data. A second non-operational satellite condition, also listed as a failure for functional dating purposes, occurs when a satellite becomes a spare. In this situation, the associated TWTAs also become non-functional, but are certainly not failed in relation to the component's lifetime. For purposes of data analyses, TWTAs in such a condition are considered truncated. Overall, TWTA statistics for components that have accrued operational time and are included in the analyses of this study are provided in Table 4. This table groups the various TWTAs by type as opposed to being grouped by host satellite serial number.

DSCS II TWTAs are identified according to the geographical range of the associated boosted signal output. They are designated either as extended coverage or narrow coverage. A further classification refers to the power

Table 3

Satellite Statistics

Satellite No.	Current Status	Launch Date/Fail Date Remarks	Operational Hours
DSCS II			
9431	1	3 Nov 71/ 2 Jun 73	13848.0
9432	1	3 Nov 71/ 8 Sep 72	7416.0
7433	D-T	13 Dec 73/ 9 Sep 76 monitored until 8 Aug 80	24000.0
7434	2	13 Dec 73/	80712.0
7437	D-T	12 May 77/ 7 May 79 monitored until 18 Dec 81	17400.0
9438	2	12 May 77/	50832.0
9441	2	13 Dec 78/	36912.0
9442	S	13 Dec 78/29 May 80	12768.0
9443	2	20 Nov 79/	28704.0
9444	2	20 Nov 79/	26376.0
9446	S	30 Oct 82/24 Nov 82	0.0
NATO III			
9363	2	22 Apr 76/	60072.0
9364	2	28 Jan 77/	21768.0
9365	2	19 Nov 78/	3888.0

Key:
1 = Failed
2 = Operational
D = Failed, TWTA continued to be monitored
T = Monitoring terminated, satellite turned off
S = Storage orbit

Table 4

Ordered Lifetime TWTA Statistics (Operational TWTAs)

	TWTA Type/SN	Satellite/ Satellite No.	Status	TWTA Operational Hours (Ordered)
ECHL--20 watt		DSCS II		
	14-2	9431	T	3888.0
	14-10	9434	F	5928.0
	14-4	9432	T	7416.0
	14-5	9431	F	9960.0
	14-21	9442	S	12192.0
	14-8	9433	T	15648.0
	14-20	9441	O	36264.0
	14-16	9437	T	40320.0
	14-1	9433	F	42624.0
	14-18	9438	O	50832.0
	14-6	9434	O	74784.0
Totals:	n=11		k=3	
NCHL--20 watt		DSCS II		
	24-17	9438	F	144.0
	24-15	9437	F	4320.0
	24-5	9432	T	7416.0
	24-27	9441	F	9168.0
	24-20	9442	S	12192.0
	24-16	9437	F	13080.0
	24-4	9431	T	13848.0
	24-21	9441	O	27096.0
	24-9	9434	F	30120.0
	24-12	9434	O	50592.0
	24-18	9438	O	50688.0
	24-10	9433	T	58272.0
Totals:	n=12		k=5	

Key

n = number of TWTAs operated
k = number of TWTAs failed
F = failed
T = monitoring terminated
O = operational

Table 4--Continued

TWTA Type/SN		Satellite/ Satellite No.	Status	TWTA Operational Hours (Ordered)
ECLL--.5 watt		DSCS II		
	34-31	9444	O	2904.0
	14-5	9432	T	7416.0
	14-24	9442	S	12192.0
	14-25	9441	O	12912.0
	14-3	9431	T	13848.0
	14-7	9433	T	17184.0
	34-33	9444	F	22896.0
	14-27	9441	F	23352.0
	34-32	9443	O	28176.0
	14-18	9437	T	40320.0
	14-6	9433	T	41088.0
	14-19	9438	O	50832.0
	14-12	9434	O	80712.0
Totals:	n=13		k=2	
NCLL--.5 watt		DSCS II		
	24-19	9438	F	2016.0
	24-3	9432	T	7416.0
	24-28	9442	S	12192.0
	24-4	9431	T	13848.0
	24-9	9433	T	17184.0
	44-30	9444	O	25800.0
	44-36	9443	O	28176.0
	24-29	9441	O	36264.0
	24-18	9437	T	40320.0
	24-8	9433	T	41088.0
	24-20	9438	O	48816.0
	24-10	9434	O	80712.0
Totals:	n=12		k=1	

Key

n = number of TWTAs operated
k = number of TWTAs failed
F = failed
T = monitoring terminated
O = operational

Table 4--Continued

TWTA Type/SN		Satellite/ Satellite No.	TWTA Status	TWTA Operational Hours (Ordered)
NATO III--20 watt		NATO III		
	002	9363	F	1.0
	006	9364	O	2016.0
	004	9365	S	3192.0
	018	9365	S	3192.0
	017	9363	F	8040.0
	009	9363	F	13176.0
	016	9364	O	19152.0
	015	9364	F	19752.0
	011	9363	O	60072.0
Totals:	n=9		k=4	

Key

n = number of TWTAs operated
k = number of TWTAs failed
F = failed
T = monitoring terminated
O = operational

consumption of the component. There are high power level TWTAs, either 20 or 40 watt devices, and low power level TWTAs which require only .5 watt. The total designator for DSCS II TWTAs, then, consists of the combination of the coverage and power designators. These designators are as follows:

1. Extended Coverage High Power Level (ECHL),
2. Narrow Coverage High Power Level (NCHL),
3. Extended Coverage Low Power Level (ECLL), and
4. Narrow Coverage Low Power Level (NCLL).

The 40 watt high level TWTA was a follow-on design prompted by inadequate performance demonstrated by the earlier 20 watt device (Sidio, 1983).

TWTAs in the DSCS II series satellite are installed as pairs, a primary and a redundant backup. The NATO III satellite, on the other hand, uses four TWTAs which are all of similar functional characteristics and power requirements.

Data Analysis

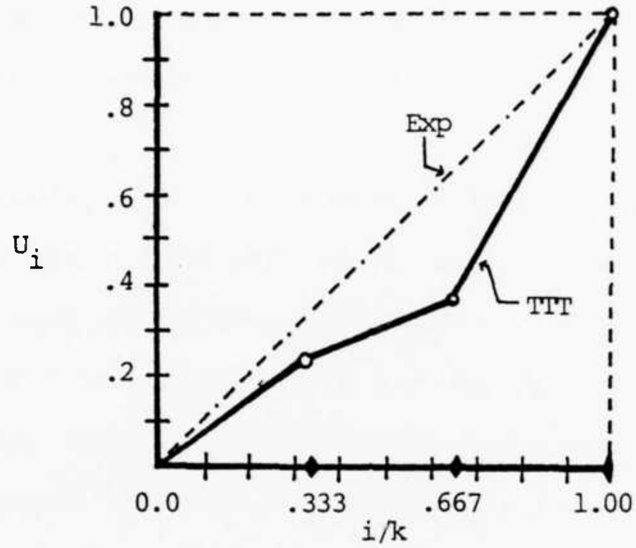
Our data analysis begins with the graphical procedures of Barlow and Campo (1975), where we construct TTT plots for the various categories of TWTAs. TTT plots are developed for the ECHL-20 watt, NCHL-20 watt, and ECLL TWTAs of the DSCS II satellite as well as for the TWTAs of the NATO III satellite. These plots are presented in

Figures 5, 6, 7, and 8. A 45-degree line, designated "Exp," is provided in each figure as a visual reference to the boundary between IFR and DFR distributions; i.e., the exponential distribution.

The ECHL TWTAs are plotted for only the 20 watt components. The variant design 40 watt ECHL TWTAs are excluded from an aggregate high power TWTA TTT plot because they may have different failure characteristics. There was a single failure among the 40 watt TWTAs (an NCHL device); however, we decline to generate a 40 watt TWTA TTT plot with such limited data.

The results of the analysis were in general similar in outcome for all ECHL categories with the exception of the TTT plot of the ECLL TWTAs. The ECHL (Figure 5), NCHL (Figure 6), and NATO III (Figure 8) TTT plots are all characteristic of components displaying DFR distributions. The ECLL TWTAs (Figure 7), on the other hand, demonstrated an IFR distribution. The ECHL, NCHL, and NATO III data is a clear illustration of components whose reliability improves with age. Conversely, the ECLL TWTA data denotes a component whose reliability decreases with age; i.e., a component that demonstrates wearout failure.

The data related to the ECHL, NCHL, and NATO III TWTAs provide a more accurate gauge of the underlying distribution of failure inherent in the TWTAs because of the higher number of observed failures. Note that the ECLL



Failed Components Ordered Lifetimes	i/k	Satellite/ TWTA Serial #	$X_{(i)}$ hrs	$T(X_{(i)})$ hrs	U_i
1	.333	9434 / 14-10	5928.0	63,168	.243
2	.667	9431 / 14-5	9960.0	96,912	.373
3	1.000	9433 / 14-1	42624.0	259,488	1.00

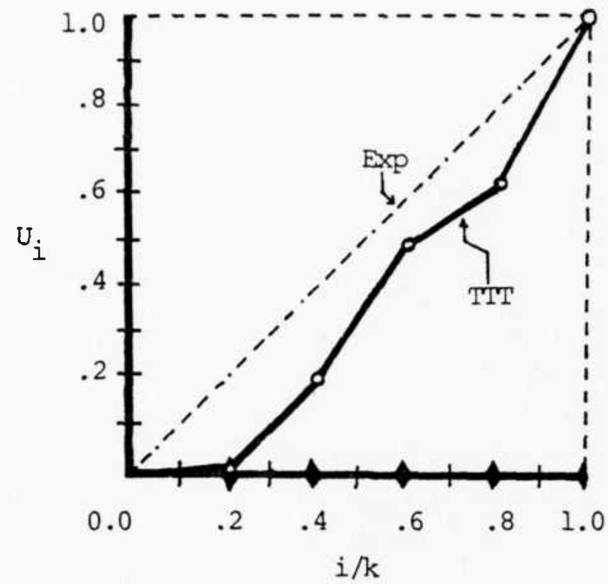
Note: $T(L) = T(X_{(3)}) = 259{,}488$ hrs.

where $k = 3$ and $n = 11$

k = no. of failures

n = no. of TWTAs with accrued operating time

Figure 5. ECHL--20 watt TWTA TTT plot for DSCS II satellite



Failed Components Ordered Lifetimes	i/k	Satellite/ TWTA Serial No.	$X_{(i)}$ hrs	$T(X_{(i)})$ hrs.	U_i
1	.2	9438 / 24-17	144.0	1728.0	.000
2	.4	9437 / 24-15	4320.0	47664.0	.209
3	.6	9441 / 24-27	9168.0	114552.0	.503
4	.8	9437 / 24-16	13080.0	144960.0	.636
5	1.0	9434 / 24-9	30120.0	227904.0	1.000

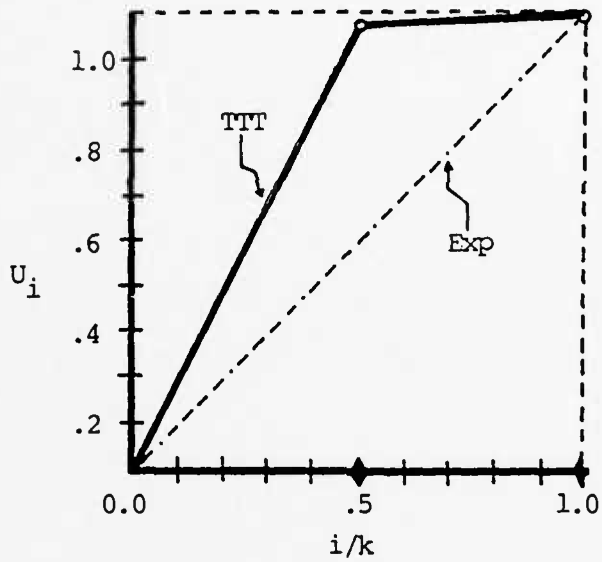
Note: $T(L) = T(X_{(5)}) = 227904$ hrs.

where $k = 5$ and $n = 12$

k = no. of failures

n = no. of TWTAs with accrued operating time

Figure 6. NCHL--20 watt TWTA TTT plot for DSCS II satellite



Failed Components Ordered Lifetimes	i/k	Satellite TWTA Serial No.	$X_{(i)}$ hrs	$T(X_{(i)})$ hrs	U_i
1	.50	9444 /34-33	22896.0	226728.0	.988
2	1.00	9441 /14-27	23352.0	229464.0	1.000

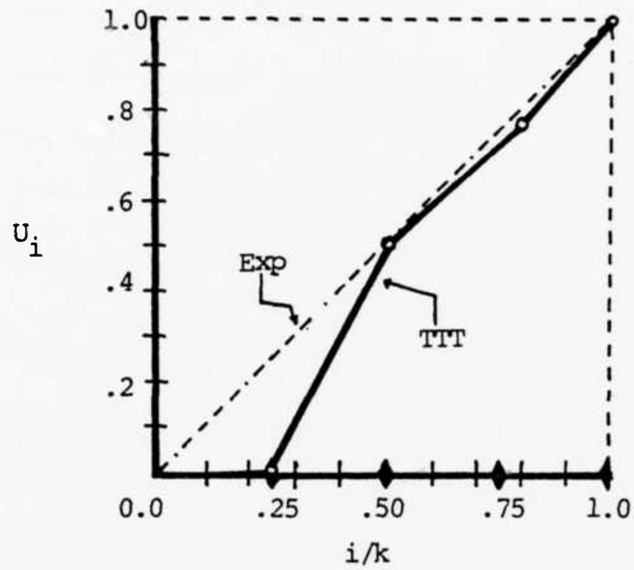
Note: $T(L) = T(X_{(2)}) = 229464.0$ hrs

where k = 2 and n = 13

k = no. of failures

n = no. of TWTAs with accrued operating time

Figure 7. ECLL--.5 watt TWTA TTT plot for DSCS II satellite



Failed Components Ordered Lifetimes	i/k	Satellite/ TWTA Serial No.	$X_{(i)}$ hrs	$T(X_{(i)})$ hrs	U_i
1	.25	9363 / 002	1.0	9.0	.0001
2	.50	9363 / 017	8040.0	48601.0	.551
3	.75	9363 / 009	13176.0	69145.0	.783
4	1.00	9364 / 015	19752.0	88273.0	1.000

Note: $T(L) = T(X_{(4)}) = 88273.0$ hrs

where $k = 4$ and $n = 9$

k = no. of failures

n = no. of TWTAs with accrued operating time

Figure 8. TWTA TTT plot for NATO III satellite

TWTA had only two failures during the period covered by the data collection. Because of scant data, we are not inclined to identify ECLL TWTAs as belonging to the IFR class. Additionally, an individual TTT plot was not developed for NCLL TWTAs. Since this type component had but a single failure during the statistic report period, no meaningful TTT plot could be constructed.

Given the general DFR results of the graphical analyses, use of the standardized cost factor to ascertain optimum maintenance intervals for the individual components was not attempted. As noted in Chapter I, corrective maintenance policies are appropriate for components displaying improved reliability with age. It is more opportune to wait for such components to fail prior to accomplishing repair or replacement, therefore negating the need for optimum maintenance interval determination.

Corollary Findings

DFR distributions are indicative of component infant mortality. A component burn-in corresponding to the DFR distribution time is generally conducted by manufacturers of DFR class components in order to eliminate these failures prior to their operational use. Our evidence of DFR class distributions for TWTA motivated us to seek information related to TWTA testing and burn-in. TRW Corporation, the DSCS II satellite builder, supplied us

with some information. A summary of our discussion related to TWTAs and their associated testing follows (Barter, 1983; Sidio, 1983).

The DSCS II TWTAs are built up from two components; the amplifier tube and the power supply. These components are individually tested by the manufacturer, a single company, and shipped to TRW for incorporation into the Traveling Wave Tube Assembly. These assemblies, referred to as components hereafter, are regarded by TRW as generically comprised of three types: 40 watt, 20 watt, and .5 watt TWTAs.

The testing of the TWTAs begins with separate tube and power supply tests by the manufacturer (Hughes). The tubes were subjected to a burn-in comprised of a time period judged adequate (by Hughes) in length as based on experience with similar other TWTA designs. The power supplies were subjected only to bench mounting and power-on operation. At TRW, the assembled TWTAs were subjected to a power-on test at vacuum. The primary goal of this latter testing was to note good workmanship and adhesion of potting compound in the area of the power supply leads rather than to properly burn-in a DFR component.

Separate life-testing of the TWTAs was accomplished concurrent to the actual satellite production and did not provide any initial informational benefit to these production units. Time constraints were cited as the reason for

this concurrency decision, system developers having had but two years, March 1969 to November 1971, constituting program start to the first launch, to meet operational requirements. There was, consequently, insufficient time to conduct life tests prior to production and launch.

Life tests conducted by TRW used no thermal cycle nor vacuum testing, conditions which would exist in the TWTA on-orbit environment (although the units slated for satellite production did receive a power-on test in vacuum). Six DSCS II TWTAs (three 20 watt and three .5 watt devices) underwent life test which ultimately spanned 10 to 11 years, from approximately 1968-69 until 1979-80. In the initial life testing, conducted at the TRW facilities, two failures were recorded, the first occurring at approximately 5000 hours and the second, initially having been noted as degraded in performance at approximately 25-30,000 hours, failing at 40,000 hours. The cause of failure in both instances was attributed to electrical shorting due to potting compound degradation. The remaining four TWTAs were removed from testing at TRW and sent to the Arnold Engineering and Test Facility to undergo further testing. There the components were subjected to conditions more like their operational environment; i.e., both thermal cycling and vacuum. An additional two failures were noted after only two or three days of testing. Marginal/improper binding (the potting compound/power supply deficiency

again) was determined to be the cause of failure. The failure mechanism was the same as in the TRW operational component testing, air inclusions fracturing the potting compound leading to electrical arcing. Vacuum inclusion in the assembly testing served to exacerbate and accelerate the failures.

The life-test findings did lead to more substantive testing of the TWTAs as well as design improvement. Burn-in was increased by incorporating a thermal cycle of 24 hours into testing, which was later expanded to two weeks of thermal cycling. Secondly, lesser potting was used on the power supply leads. These initial actions led to improvements in the follow-on 40 watt TWTAs. Current NATO satellite TWTA design has totally eliminated the need for potting compound by use of non-potted "flying leads."

In reflection, the TWTA improvements were warranted, yet they did not come until the program was significantly advanced, note again the 10-year life test period.

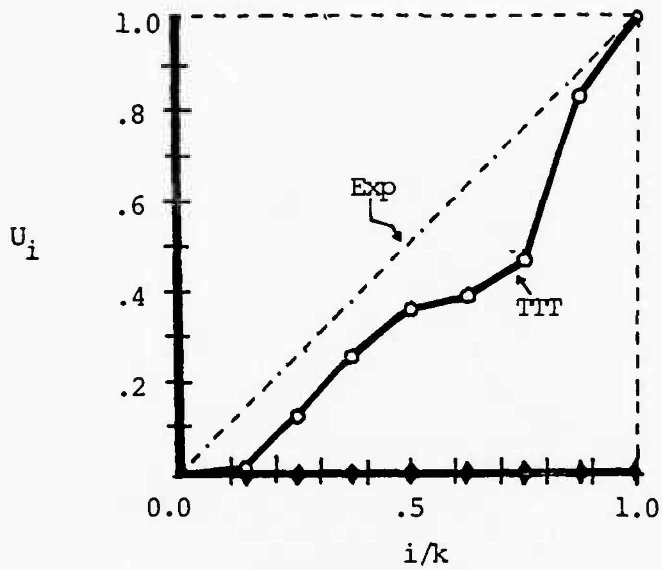
The TRW representatives made several cogent remarks as follows:

1. Qualification and testing need to be accomplished prior to the start of a space program. Similarly, procurements (speaking of TWTAs) need to be initiated prior to system start.

2. Follow-on systems/components do not necessarily reap the benefits gleaned from previous systems/components and often, as a consequence, replicate errors and problems seen in the past. This reference related to the follow-on TWTA design initiated for the NATO III satellite which, due to a minor specification change, led to essentially a restart of the experience curve with the same component.

In conclusion, the TRW comments coincided with the findings of our graphical analyses in that indeed DFR distributions were probable if not expected. Earlier version TWTA life data was used to evaluate DSCS II and NATO III TWTA burn-in requirements even though the DSCS II and NATO III operating environments and designs were different. Thus, one might expect inadequate burn-in in this case and in subsequent programs where restrictive program timing is the norm.

TRW categorizes the DSCS II TWTAs according to their power requirements, the signal coverage being noted as a minor difference in tuning. Hence all 20 watt devices are viewed as the same type TWTA as are the .5 watt TWTAs (Sidio, 1983). Given the TRW generic grouping of TWTAs, aggregate TTT plots of 20 watt and .5 watt TWTAs are provided in Figures 9 and 10. The aggregate 20 watt TTT plot again reflects the similar underlying DFR distributions of its constituents, ECHL and NCHL-20 watt TWTAs. The aggregate .5 watt plot constituted of the .5 watt ECLL and



Note: Total 20 Watt TWTA Failures = k = 8

Failed Components Ordered Lifetimes	i/k	Satellite/ TWTA Serial No.	$X_{(i)}$ hrs	$T(X_{(i)})$ hrs	U_i
1	.125	9438 / 24-17	144.0	3312.0	.125
2	.250	7437 / 24-15	4320.0	94752.0	.25
3	.375	9434 / 14-10	5928.0	126912.0	.375
4	.500	9441 / 24-27	9168.0	184968.0	.5
5	.625	9431 / 14-5	9960.0	197640.0	.625
6	.750	9437 / 24-16	13080.0	242664.0	.75
7	.875	9434 / 24-9	30120.0	413376.0	.875
8	1.000	9433 / 14-1	42624.0	504774.0	1.00

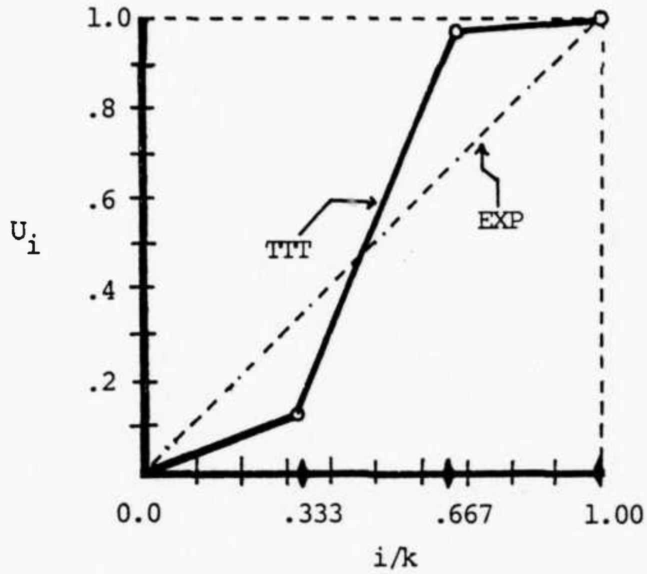
Note: $T(L) = T(X_{(8)}) = 504774.0$ hrs

where k = 8 and n = 23

k = no. of failures

n = no. of TWTAs with accrued operating time

Figure 9. Aggregate 20 watt TWTA TTT plot for DSCS II satellite



Note: Total .5 Watt TWTA Failures = k = 3

Failed Components Ordered Lifetimes	i/k	Satellite/ TWTA Serial No.	$X_{(i)}$ hrs	$T(X_{(i)})$ hrs	U_i
1	.333	9438 / 24-19	2016.0	50400.0	.113
2	.667	9444 / 34-33	22896.0	439656.0	.987
3	1.000	9441 / 14-27	23352.0	445584.0	1.000

Note: $T(L) = T(X_{(3)}) = 445584.0$ hrs

where k = 3 and n = 25

k = no. of failures

n = no. of TWTAs with accrued operating time

Figure 10. Aggregate .5 watt TWTA TTT plot for DSCS II satellite

NCLL TWTAs displays a crossing of the exponential distribution reference line by the TTT plot, illustrating the possibility that the data is exponential for the aggregate plot. Due to the limited number of data points, three failures in total, we decline to investigate whether this data is exponential. The aspect of 45-degree reference line crossings is discussed by Barlow and Campo, "Total Time on Test Processes and Applications to Failure Data Analysis" (1975), and Bergman, "Crossings in the Total Time on Test Plot," Scandinavian Journal of Statistics, Vol. 4, 1977.

CHAPTER IV

DISCUSSION, RECOMMENDATIONS, AND CONCLUSION

The primary goals of this research effort were to determine whether preventive maintenance on space systems was a viable possibility, and given successful accomplishment of this objective, to determine whether an optimum maintenance interval could be estimated for scheduling purposes. Given the requirements established by AFM 1-6 and the potential provided by the STS, future maintenance concepts could well use such a tool.

Initially, we sought data on several different components which we thought would exhibit wearout failure in their operational state. However, due to data limitations, the scope of our effort was reduced to one such component, the Traveling Wave Tube Assembly (TWTA).

Discussion

The use of the Total-Time-on-Test graphical procedure provides evidence that DSCS II and NATO III on-orbit TWTAs have DFR class failure distributions. Given these DFR distributions, further analyses using the standardized costs were deemed inappropriate; therefore, optimum maintenance intervals were not computed. Because of the narrowed scope and the overall DFR distributions the

secondary objectives related to system complexity and component grouping for maintenance interval determination were not approached either.

The corollary findings were a surprise. They served to underscore the usefulness of the TTT procedures for their empirical evaluational characteristics. Having started with a component generally believed to be failing based on wearout, the graphical analysis pointed instead toward one that was suffering infant mortality which was confirmed by discussions related to TWTA design and testing. Other positive points realized through use of the TTT plotting technique are as follows:

1. The procedures were simple, easily used, providing readily discernable results.

2. As stated, the procedure did answer the question of whether preventive maintenance was applicable (albiet a somewhat restricted view with just one component). While the answer provided was negative on this issue, it stressed the need to evaluate components and conditions fully prior to assuming a maintenance requirement and an associated spare part level are established.

3. By pointing out the risk with incomplete testing, the procedure has stressed the need to accomplish more complete testing and system analyses prior to operational commitment of such components as the TWTA. Additionally, the advantages of using existing components and related

lessons learned in follow-on requirements was emphasized. A study of the TWTA points out the importance of reliability considerations to the overall design and acquisition processes.

Recommendations for Further Study

Recommendations stemming from this study relate primarily to continuing attempts to gather operational data on space system components with the goal of performing multiple component and system analyses. As noted throughout this study, such analyses would also serve to clarify performance/failure characteristics of the components.

A broad area of application also exists in non-space systems and components. Graphical analyses could be performed on many complex/high-reliability components and systems in the areas of aircraft and equipment maintenance. By use of such methodologies planners and managers could avoid the limiting confines of subjective estimates and back up their decision logic with empirical evidence.

The applicability of graphical analysis as a maintenance interval determining technique should be evaluated within the decision logic of the Reliability Centered Maintenance concept. It would seem to be ideally suited for on-condition or hard time maintenance decision requirements.

Conclusions

Preventive maintenance as an appropriate category of maintenance on some space system TWTAs was demonstrated not to be the method of choice as determined within the confines of this study. Provided that corrective maintenance was therefore chosen, logic would dictate that the proper maintenance procedures would revolve about corrective repair and replacement schemes. It is noted that this conclusion is based on but a single type component and that further analyses, given the availability of additional component type data, may alter this study's findings.

The Total-Time-on-Test plot has been demonstrated to be both a functionally useful and flexible procedure well worthy of further consideration in future related studies.

There were other candidate components which were unable to be evaluated for want of data. If the proposition of maintenance in space is to be taken as a serious consideration, Air Force management should re-evaluate its data base requirements in order to support analyses of this important issue.

APPENDIX

TWTA STATISTICS REPORT

DISTRIBUTION LIST FOR TITA STATISTICS 1 MAR 83

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SATELLITE STATISTICS

COMMENTS

ORBITAL OPERATION OF REDUNDANT UNITS WAS VERIFIED DURING POST LAUNCH CHECK OUT AND TYPICALLY RECEIVED 300 HOURS OF OPERATING TIME PRIOR TO OPERATIONAL USE.

9435/9436 LAUNCHED 20 MAY 1975, FAILURE DUE TO BOOSTER MALFUNCTION

9439/9440 LAUNCHED 25 MAR 1978, FAILURE DUE TO BOOSTER MALFUNCTION

THIS RUN CONTAINS NON-BIASED DATA

```
$INPUT
T7FAIL  = .4E+01,
NATFAIL = 0.0,
ISAT    = 15,
IPUNCH  = 0,
IPRNT   = 0,
D3FAIL  = 0.0,
$END
```

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM	777
SATELLITE ID	9431
LAUNCH DATE	3 NOV 71
SATELLITE LONGITUDE	***
DATE OF FAILURE	2 JUNE 73
CAUSE OF FAILURE	LOSS OF POWER TO DESPIN SECTION
TOTAL S/C OPTIME (HRS)	13848.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
ECHL1-20	14-5	9960.00	22 DEC 72	PROBABLE HIGH VOLTAGE FAILURE
ECHL2-20	14-2	3868.00		SEE NOTE (1)
NCHL1-20	24-4	13848.00		
NCHL2-20	24-3	0.00		SEE NOTE (1)
ECLL1-.5	14-3	13848.00		
ECLL2-.5	14-4	0.00		SEE NOTE (1)
NCLL1-.5	24-4	13848.00		
NCLL2-.5	24-5	0.00		SEE NOTE (1)

COMMENTS

(1) ECHL2, NCHL2, ECLL2, NCLL2 ON 264 HOURS POST LAUNCH CHECK-OUT

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM 777

SATELLITE ID 9432

LAUNCH DATE 3 NOV 71

SATELLITE LONGITUDE ***

DATE OF FAILURE 8 SEPT 72

CAUSE OF FAILURE POWER DISTRIBUTION FAILURE

TOTAL S/C OPTIME (HRS) 7416.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE
ECHL1-20	14-4	7416.00	
ECHL2-20	14-3	0.00	SEE NOTE (1)
NCHL1-20	24-5	7416.00	
NCHL2-20	24-6	0.00	SEE NOTE (1)
ECLL1-.5	14-5	7416.00	
ECLL2-.5	14-2	0.00	SEE NOTE (1)
NCLL1-.5	24-3	7416.00	
NCLL2-.5	24-6	0.00	SEE NOTE (1)

COMMENTS

(1) ECHL2, NCHL2, ECLL2, NCLL2 ON 360 HOURS POST LAUNCH CHECK-OUT

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM	777
SATELLITE ID	9433
LAUNCH DATE	13 DEC 73
SATELLITE LONGITUDE	***
DATE OF FAILURE	9 SEPT 76
CAUSE OF FAILURE	SPIN-UP (SEE NOTE 3)
TOTAL S/C OPTIME (HRS)	24000.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
ECHL1-20	14-1	42624.00	25 OCT 78	PROBABLE HIGH VOLTAGE POWER SUPPLY FAILURE
ECHL2-20	14-8	15648.00		SEE NOTE (1)
NCHL1-20	24-10	58272.00		
NCHL2-20	24-8	0.00		SEE NOTE (1)
ECLL1-.5	14-6	41088.00	OFF 8/78	TWTA TURNED OFF 22 AUG 1978. SEE NOTE (2)
ECLL2-.5	14-7	17184.00		SEE NOTE (1)
NCLL1-.5	24-8	41088.00	OFF 8/78	TWTA TURNED OFF 22 AUG 1978. SEE NOTE (2)
NCLL2-.5	24-9	17184.00		SEE NOTE (1)

COMMENTS

(1) ECHL2, NCHL2, ECLL2, NCLL2 ON 360 HOURS POST LAUNCH CHECK-OUT

(2) ECLL1 AND NCLL1 TURNED-OFF ON 22 AUG 1978.
ECLL2 AND NCLL2 TURNED ON FOR EVALUATION.

(3) TWTA OPERATION MONITORED UNTIL 8 AUG 1980 AT WHICH TIME
TWTA OPERATION MONITORING TERMINATED.

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM	777
SATELLITE ID	9434
LAUNCH DATE	13 DEC 73
SATELLITE LONGITUDE	60 DEG. EAST
DATE OF FAILURE	
CAUSE OF FAILURE	
TOTAL S/C OPTIME (HRS)	80712.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
ECHL1-20	14-10	5928.00	17 AUG 74	PROBABLE HIGH VOLTAGE FAILURE
ECHL2-20	14-6	74784.00		SEE NOTE (1)
NCHL1-20	24-9	30120.00	22 MAY 77	PROBABLE POWER SUPPLY FAILURE
NCHL2-20	24-12	50592.00		SEE NOTE (1)
ECLL1-.5	14-12	80712.00		
ECLL2-.5	14-11	0.00		SEE NOTE (1)
NCLL1-.5	24-10	80712.00		
NCLL2-.5	24-7	0.00		SEE NOTE (1)

COMMENTS

(1) ECHL2, NCHL2, ECLL2, NCLL2 ON 336 HOURS POST LAUNCH CHECK-OUT

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM	777
SATELLITE ID	9437
LAUNCH DATE	12 MAY 77
SATELLITE LONGITUDE	13 DEG/DAY DRIFT
DATE OF FAILURE	7 MAY 79
CAUSE OF FAILURE	*** SEE NOTE 2 ***
TOTAL S/C OPTIME (HRS)	17400.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
ECHL1-20	14-14	0.00		SEE NOTE (1)
ECHL2-20	14-16	40320.00	OFF 12/81	S/C POWER SUBSYSTEM FAILURE, SEE NOTE (2)
NCHL1-20	24-15	4320.00	07 MAY 79	PROBABLE HIGH VOLTAGE FAILURE
NCHL2-20	24-16	13080.00	8 NOV 78	PROBABLE POWER SUPPLY FAILURE
ECLL1-.5	14-17	0.00		SEE NOTE (1)
ECLL2-.5	14-18	40320.00	OFF 12/81	CATHODE CURRENT DEGRADING
NCLL1-.5	24-17	0.00		SEE NOTE (1)
NCLL2-.5	24-18	40320.00	OFF 12/81	S/C POWER SUBSYSTEM FAILURE, SEE NOTE (2)

COMMENTS

(1) ECHL1, NCHL1, ECLL1, NCLL1, ON FOR POST LAUNCH CHECK-OUT 12 MAY TO 16 MAY 77. (120 HOURS)

(2) 7 MAY 79 N.C. CHANNEL FAILURE CORRESPONDED TO S/C CONTRACTUAL FAILURE HOWEVER E.C. CHANNEL CONTINUED TO OPERATE UNTIL FAILURE IN SHUNT REGULATOR CIRCUIT, 18 DEC 1981. SATELLITE BOOSTED INTO SUPERSYNCHRONOUS ORBIT (+ 600 NM.).

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM	777
SATELLITE ID	9438
LAUNCH DATE	12 MAY 77
SATELLITE LONGITUDE	175 DEG. EAST
DATE OF FAILURE	
CAUSE OF FAILURE	
TOTAL S/C OPTIME (HRS)	50832.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
ECHL1-20	14-17	0.00		SEE NOTE (1)
ECHL2-20	14-18	50832.00		
NCHL1-20	24-17	144.00	20 MAY 77	PROBABLE HIGH VOLTAGE FAILURE
NCHL2-20	24-18	50688.00		
ECLL1-.5	14-20	0.00		SEE NOTE (1)
ECLL2-.5	14-19	50832.00		CATHODE CURRENT DEGRADING
NCLL1-.5	24-20	48816.00		
NCLL2-.5	24-19	2016.00	28 AUG 77	PROBABLE POWER SUPPLY HEATER CIRCUIT FAILURE

COMMENTS

(1) ECHL1, ECLL1, NCLL1 ON FOR POST LAUNCH CHECK-OUT 12 MAY TO 4 JUNE 77 (550 HOURS)

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM 777

SATELLITE ID 9441

LAUNCH DATE 13 DEC 78

SATELLITE LONGITUDE 135 DEG. WEST

DATE OF FAILURE

CAUSE OF FAILURE

TOTAL S/C OPTIME (HRS) 36912.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
ECHL1-20	14-24	0.00		SEE NOTE (1)
ECHL2-20	14-20	36264.00		
NCHL1-20	24-21	27096.01		SEE NOTE (1)
NCHL2-20	24-27	9168.00	26 JAN 80	PROBABLE POWER SUPPLY FAILURE
ECLL1-.5	14-25	12912.00		SEE NOTE (1)
ECLL2-.5	14-27	23352.00	09 SEP 81	EXCESSIVE GAIN REDUCTION, SEE NOTE (2)
NCLL1-.5	44-32	0.00		SEE NOTE (1)
NCLL2-.5	24-29	36264.00		

COMMENTS

(1) ECHL1, NCHL1, ECLL1, NCLL1, ON 4 JAN 79 TO 9 JAN 79 POST LAUNCH CHECK-OUT. (120 HOURS)

(2) ECLL2 CATHODE CURRENT TELEMETRY (IK) FAILED 30 JUNE 79, TWTA TURNED OFF 9 SEP 1981.

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM	777
SATELLITE ID	9442
LAUNCH DATE	13 DEC 78
SATELLITE LONGITUDE	66 DEG. EAST
DATE OF FAILURE	29 MAY 80
CAUSE OF FAILURE	VEHICLE IN STORAGE ON-ORBIT
TOTAL S/C OPTIME (HRS)	12768.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
ECHL1-20	14-19	0.00		SEE NOTE (1)
ECHL2-20	14-21	12192.00	OFF 5/80	TWTA TURNED OFF 29 MAY 1980
NCHL1-20	24-26	0.00		SEE NOTE (1)
NCHL2-20	24-20	12192.00	OFF 5/80	TWTA TURNED OFF 29 MAY 1980
ECLL1-.5	14-28	0.00		SEE NOTE (1)
ECLL2-.5	14-24	12192.00	OFF 5/80	TWTA TURNED OFF 29 MAY 1980
NCLL1-.5	24-27	0.00		SEE NOTE (1)
NCLL2-.5	24-28	12192.00	OFF 5/80	TWTA TURNED OFF 29 MAY 1980

COMMENTS

(1) ECHL1, NCHL1, ECLL1, NCLL1 ON 3 JAN 79 TO 6 JAN 79 POST LAUNCH CHECK-OUT.
(72 HOURS)

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM 777

SATELLITE ID 9443

LAUNCH DATE 20 NOV 79

SATELLITE LONGITUDE 131 DEG. WEST

DATE OF FAILURE

CAUSE OF FAILURE

TOTAL S/C OPTIME (HRS) 28704.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
ECHL1-40	14-2	0.00		SEE NOTE (1)
ECHL2-40	14-8	28176.00		
NCHL1-40	24-1	17784.00		TURNED ON 18 FEB 81 - SEE NOTE 2
NCHL2-40	24-6	10392.00	18 FEB 81	FAILED 18 FEBRUARY 1981
ECLL1-.5	34-30	0.00		SEE NOTE (1)
ECLL2-.5	34-32	28176.00		
NCLL1-.5	44-33	0.00		SEE NOTE (1)
NCLL2-.5	44-36	28176.00		

COMMENTS

(1) ECHL1, NCHL1, ECLL1, NCLL1 ON 10 DEC TO 12 DEC 79 POST LAUNCH CHECK-OUT. (48 HOURS)

(2) NCHL1-40 - NC CHANNEL SHOWING INTERMITTANT RF SPIKING STARTING 20 FEB 81. BACK IN SERVICE AS OF AUG 81

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM	777
SATELLITE ID	9446
LAUNCH DATE	30 OCT 82
SATELLITE LONGITUDE	DRIFTING
DATE OF FAILURE	24 NOV 82
CAUSE OF FAILURE	VEHICLE IN STORAGE ON-ORBIT
TOTAL S/C OPTIME (HRS)	600.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE
ECHL1-40	34-35	0.00	SEE NOTE (1)
ECHL2-40	34-37	0.00	SEE NOTE (1)
NCHL1-40	44-31	0.00	SEE NOTE (1)
NCHL2-40	44-34	0.00	SEE NOTE (1)
ECLL1-.5	14-5	0.00	SEE NOTE (1)
ECLL2-.5	14-1	0.00	SEE NOTE (1)
NCLL1-.5	24-7	0.00	SEE NOTE (1)
NCLL2-.5	24-3	0.00	SEE NOTE (1)

COMMENTS

(1) ECHL1, NCHL1, ECLL1, NCLL1 ON 15 NOV 82, POST LAUNCH CHECK-OUT. (24 HOURS)
ECHL2, NCHL2, ECLL2, NCLL2 ON 16 NOV - 24 NOV 82, POST LAUNCH CHECK-OUT. (192 HOURS)

DSCS-II TWTA ORBITAL LIFE, HOURS (TO 1 MAR 83)

	9433	9434	9437	9438	9441	9442	9443	9444	9446
ECHL1	42624.	5928.	0.	0.	0.	0.	0.	0.	0.
ECHL2	15648.	74784.	40320.	50832.	36264.	12192.	28176.	25800.	0.
NCHL1	58272.	30120.	4320.	144.	27096.	0.	17784.	0.	0.
NCHL2	0.	50592.	13080.	50680.	9168.	12192.	10392.	25800.	0.
ECLL1	41088.	80712.	0.	0.	12912.	0.	0.	2904.	0.
ECLL2	17184.	0.	40320.	50832.	23352.	12192.	28176.	22896.	0.
NCLL1	41088.	80712.	0.	48816.	0.	0.	0.	0.	0.
NCLL2	17184.	0.	40320.	2016.	36264.	12192.	28176.	25800.	0.

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM	DSCS III
SATELLITE ID	6451
LAUNCH DATE	30 OCT 82
SATELLITE LONGITUDE	DRIFTING
DATE OF FAILURE	
CAUSE OF FAILURE	
TOTAL S/C OPTIME (HRS)	2928.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE
CH3-1-10	H -004	2376.00	SEE NOTE (1)
CH3/4-10	WJ -106	0.00	
CH4-1-10	H -009	2376.00	SEE NOTE (1)
CH5-1-10	H -005	2376.00	SEE NOTE (1)
CH5/6-10	WJ -107	0.00	
CH6-1-10	H -007	2376.00	SEE NOTE (1)
CH1-1-40	WJ -005	0.00	
CH1-2-40	H -010	2376.00	SEE NOTE (1)
CH2-1-40	WJ -003	0.00	
CH2-2-40	H -006	2376.00	SEE NOTE (1)

COMMENTS

(1) H-TWTA TURN-ON 22 NOV 1982

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM NATO III

SATELLITE ID 9363

LAUNCH DATE 22 APR 76

SATELLITE LONGITUDE 18.0 DEG. WEST (+- 0.5 DEG.)

DATE OF FAILURE

CAUSE OF FAILURE *** SEE NOTE (4) ***

TOTAL S/C OPTIME (HRS) 60072.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
TWTA-1 (20W)	017	8040.0	23 MAR 77	PROBABLE HIGH VOLTAGE FAILURE, SEE NOTE (1,3)
TWTA-2 (20W)	009	13176.0	22 SEP 78	PROBABLE HIGH VOLTAGE FAILURE, SEE NOTE (3)
TWTA-3 (20W)	002	1.0	22 SEP 78	PROBABLE HIGH VOLTAGE FAILURE, SEE NOTE (2,3)
TWTA-4 (20W)	011	60072.0		

COMMENTS

(1) PRE-LAUNCH TEST, TWTA-1 (S/N 007) REPLACED BY (S/N 017) 27 MAR 76.

(2) TWTA-3 (S/N 002) ON-TIME BEFORE FAILURE, 7 MIN.

(3) TWTA-1 (S/N 017), TWTA-2 (S/N 009) AND TWTA-3 (S/N 002) - A TURN-ON ATTEMPT WAS MADE ON 20 APR 79. UNITS WOULD NOT TURN-ON.

(4) PER AGREEMENT WITH NATO USERS, SATELLITE CONSIDERED NOT FAILED EVEN THOUGH ORIGINAL RELIABILITY REQUIREMENTS WERE NOT SATISFIED.

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM NATO III

SATELLITE ID 9364

LAUNCH DATE 28 JAN 77

SATELLITE LONGITUDE 21.0 DEG. WEST (+- 0.5 DEG.)

DATE OF FAILURE

CAUSE OF FAILURE

TOTAL S/C OPTIME (HRS) 21768.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
TWTA-1 (20W)	015	19752.0	7 DEC 82	PROBABLE HIGH VOLTAGE FAILURE, SEE NOTE(2,3)
TWTA-2 (20W)	006	2016.0		TURN-ON 7 DEC 82, SEE NOTE (1)
TWTA-3 (20W)	014	0.0		SEE NOTE (1)
TWTA-4 (20W)	016	19152.0		REACTIVATED 6 DEC 82, SEE NOTE (4)

COMMENTS

(1) TWTA S 2 AND 3 ON 14 FEB - 3 MAR 77 POST LAUNCH CHECK-OUT.
(216 AND 240 HOURS RESPECTIVELY)

(2) TUBES TURNED OFF - VEHICLE IN STORAGE ON-ORBIT - 1 MAY 1979

(3) TWTA-1 TURN-ON ATTEMPT 7 DEC 82 - BUS BREAKER OPENED AT HIGH VOLTAGE TURN-ON

(4) TWTA-4 TURNED-OFF 11 JAN 79.

SATELLITE STATISTICS AS OF 1 MAR 83

PROGRAM NATO III

SATELLITE ID 9365

LAUNCH DATE 19 NOV 78

SATELLITE LONGITUDE 50.0 DEG. WEST (+- 3.0 DEG.)

DATE OF FAILURE 30 APR 79

CAUSE OF FAILURE SEE COMMENT

TOTAL S/C OPTIME (HRS) 3888.0

TWTA	S/N	OP TIME/HRS	TWTA FAIL DATE	
TWTA-1 (20W)	013	0.0		SEE NOTE (1)
TWTA-2 (20W)	004	3192.0	OFF 4/79	TWTA TURNED OFF 30 APRIL 1979, SEE NOTE (2)
TWTA-3 (20W)	018	3192.0	OFF 4/79	TWTA TURNED OFF 30 APRIL 1979, SEE NOTE (2)
TWTA-4 (20W)	001	0.0		SEE NOTE (1)

COMMENTS

(1) TWTA S 1 AND 4 12/3/78 - 12/18/78 POST LAUNCH CHECKOUT. (360 HOURS)

(2) TUBES TURNED OFF - VEHICLE IN STORAGE ON-ORBIT - 30 APR 1979

```
ALPHA, BETA =   37155.79      1.02  FOR HLTWTA S

ALPHA, BETA =   68762.62      1.46  FOR LLTWTA S

ALPHA, BETA =   41416.[illegible]      1.44  FOR FWTWTA S
```

SUMMARY DATA

PROGRAM 777 TOTAL S/C OP HOURS 299568.0

NUMBER OF SATELLITES 11.0

NUMBER OF S/C FAILURES 4.0

MTTF AT 60 PERCENT LCL 57067.7

PROGRAM NATO III TOTAL S/C OP HOURS 85723.0

NUMBER OF SATELLITES 3.0

NUMBER OF S/C FAILURES 0.0

MTTF AT 60 PERCENT LCL 93700.7

PROGRAM DSCS III TOTAL S/C OP HOURS 2928.0

NUMBER OF SATELLITES 1.0

NUMBER OF S/C FAILURES 0.0

MTTF AT 60 PERCENT LCL 3200.3

SUM OF ALL HLTWTA S OP TIME (HRS) 705385.0

NUMBER OF HLTWTA (OPERATIONALLY USED) 32.0

TOTAL NUMBER OF FAILURES 12.0

HLTWTA MTTF AT 60 PER CENT LCL = 51845.80
HLTWTA MTTF AT 60 PER CENT LCL WITH 150000 HOUR CATHODE WEAROUT 48973.6

SUM OF ALL LLTWTA S OP TIME (HRS) 707664.0

NUMBER OF LLTWTA (OPERATIONALLY USED) 25.0

TOTAL NUMBER OF FAILURES 3.0

LLTWTA MTTF AT 60 PER CENT LCL = 169603.5
LLTWTA MTTF AT 60 PER CENT LCL WITH 150000 HOUR CATHODE WEAROUT 99564.8

SUM OF ALL TWTA-40S OP TIME (HRS) 112704.0

NUMBER OF TWTA-40 (OPERATIONALLY USED 7.0

TOTAL NUMBER OF FAILURES 1.0

TWTA-40 MTTF AT 60 PER CENT LCL = 55783.48
FWTWTA MTTF AT 60 PER CENT LCL WITH 150000 HOUR CATHODE WEAROUT 51996.7

SUM OF ALL TEN WATT TWTA S OP TIME (HRS) 9504.0

NUMBER OF TEN WATT TWTA S (OPERATIONALLY USED) 4.0

TOTAL NUMBER OF FAILURES 0.0

TEN WATT TWTA MTTF AT 60 PER CENT LCL = 10387.87
TEN WATT TWTA MTTF AT 60 PER CENT LCL WITH 150000 HOUR CATHODE WEAROUT 10367.9

SCOPE 2 LOAD MAP LOADER VERSION 1.0 03/04/83 11.15.38. PAGE 1

PROGRAM WILL BE ENTERED AT SATFAIL (221) SCM LENGTH 47436 LCM LENGTH 0

BLOCK	ADDRESS	LENGTH	FILE	DATE	PROCESSOR	VER	LEVEL	HARDWARE	COMMENTS
SATFAIL	110	22706	LGO	02/07/83	FTN	4.6	452	I	PROGRAM OPT=1
MTTF	23016	153	LGO	02/07/83	FTN	4.6	452	I	SUBROUTINEOPT=1
CATNUM	23171	776	LGO	02/07/83	FTN	4.6	452	I	SUBROUTINEOPT=1
WEIBL	24167	2614	LGO	02/07/83	FTN	4.6	452	I	SUBROUTINEOPT=I
GAUSS	26203	242	LGO	02/07/83	FTN	4.6	452	I	SUBROUTINEOPT=1
CUMPLOT	26445	I2II3	LGO	02/07/83	FTN	4.6	452	I	SUBROUTINEOPT=1
/STP.END/	40560	1	SL-FORTX						
/FCL.C./	4056I	23	SL-FORTX						
/Q8.IO./	40604	136	SL-FORTX						
Q8NTRY=	40742	I	SL-FORTX	02/09/78	COMPASS	3.	3-430		FCL INITIALIZATION ROUTINE.
COMIO=	40743	60	SL-FORTX	02/09/78	COMPASS	3.	3-452		COMMON CODED I/O ROUTINES AND CONSTANTS.63-CHAR
DECODE=	41023	115	SL-FORTX	02/09/78	COMPASS	3.	3-452		FORMATTED READ FROM CORE.
ENDFIL=	41140	45	SL-FORTX	02/09/78	COMPASS	3.	3-452		WRITE END OF LOGICAL FILE MARK.
EOF	41205	20	SL-FORTX	02/09/78	COMPASS	3.	3-452		TEST FOR END OF FILE STATUS.
FECMSK=	41225	4I	SL-FORTX	02/09/78	COMPASS	3.	3-452		INITIALIZE CONSTANTS.
FLTIN=	41266	156	SL-FORTX	02/09/78	COMPASS	3.	3-452		COMMON FLOATING INPUT CONVERTER.
FLTOUT=	41444	315	SL-FORTX	02/09/78	COMPASS	3.	3-452		COMMON FLOATING OUTPUT CODE
FMTAP=	4176I	373	SL-FORTX	02/09/78	COMPASS	3.	3-452		CRACK APLIST AND FORMAT FOR KODER/KRAKER.
FORSYS=	42354	533	SL-FORTX	02/09/78	COMPASS	3.	3-452		FORTRAN OBJECT LIBRARY UTILITIES.
FORUTL=	43107	44	SL-FORTX	02/09/78	COMPASS	3.	3-452		FCL MISC. UTILITIES.
GETFIT=	43153	43	SL-FORTX	02/09/78	COMPASS	3.	3-452		LOCATE AN FIT GIVEN A FILE NAME.
INCOM=	43216	262	SL-FORTX	02/09/78	COMPASS	3.	3-452		COMMON INPUT FORMATTING CODE
INPC=	43500	173	SL-FORTX	02/09/78	COMPASS	3.	3-452		FORMATTED READ FORTRAN RECORD.
KODER=	43673	467	SL-FORTX	02/09/78	COMPASS	3.	3-452		OUTPUT FORMAT INTERPRETER.
KRAKER=	44362	435	SL-FORTX	02/09/78	COMPASS	3.	3-452		PROCESS FORMATTED FORTRAN INPUT.
NAMIN=	45017	573	SL-FORTX	02/09/78	COMPASS	3.	3-452		NAMELIST INPUT ROUTINE.
NAMOUT=	45612	267	SL-FORTX	02/09/78	COMPASS	3.	3-452		NAMELIST OUTPUT ROUTINE.
/IO.BUF./	46101	227	SL-FORTX						
OUTB=	46330	215	SL-FORTX	02/09/78	COMPASS	3.	3-452		BINARY WRITE FORTRAN RECORD.
OUTC=	46545	174	SL-FORTX	02/09/78	COMPASS	3.	3-452		FORMATTED WRITE FORTRAN RECORD.
OUTCOM=	46741	204	SL-FORTX	02/09/78	COMPASS	3.	3-452		COMMON OUTPUT CODE
ALOG	47145	77	SL-FORTX	02/09/78	COMPASS	3.	3-452		COMPUTE COMMON AND NATURAL LOGARITHMS. OPT=ALL.
EXP	47244	100	SL-FORTX	02/09/78	COMPASS	3.	3-452		EXPONENTIAL FUNCTION. E TO POWER X. OPT=ALL.
SYSAID=	47344	1	SL-FORTX	02/09/78	COMPASS	3.	3-452		LINK BETWEEN SYS=AID AND INITIALIZATION CODE.
SYS=1ST	47345	62	SL-FORTX	02/09/78	COMPASS	3.	3-452		MATH LIBRARY LINK TO ERROR MESSAGE PROCESSOR.
XTOY=	47427	7	SL-FORTX	02/09/78	COMPASS	3.	3-452		REAL TO REAL EXPONENTIATION.

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